Summer School on Muon Spin Rotation and Beta Detected NMR

(an overview)

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The TRIUMF Centre for Molecular and Materials Science

http://musr.ca

Objectives

- Indoctrination
- What you should be able to do by the end:
  - read, interpret and evaluate μSR papers
  - participate productively in experiments
  - suggest new experiments
- Have Fun!

The Probes

The Positive Muon (μ^+)

- a heavier (200x) positively charged electron-like lepton
- unstable to radioactive beta decay with an exponential lifetime τ = 2.2 microseconds
- beta decay yields a high energy positron that is easy to detect
- See L2,3 Brewer

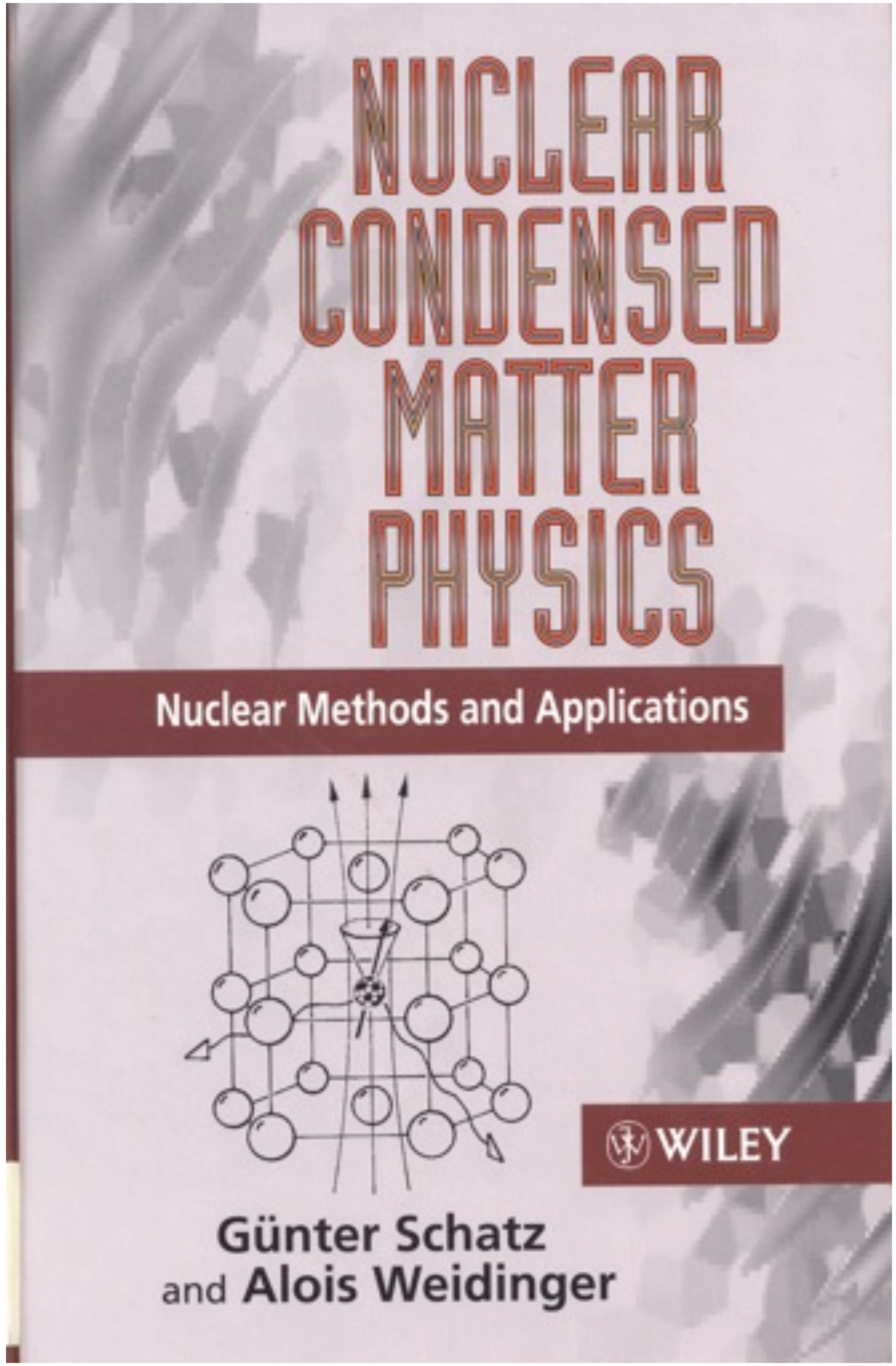
Lithium-8 ($^8Li^+$)

- A heavy isotope of the element lithium
- Unstable to radioactive beta decay with a lifetime of 1.2 seconds
- Beta decay yields a high energy electron that is easy to detect
- See L15, 17 (Kiefl)

- Unlike neutrons or Xrays, the probes are **charged** (see L18, Uemura)
- Beam transport via electromagnetic fields
- Strong interaction with matter: not very penetrating (thin windows)
- The probes are detected by their radioactive decay

Nuclear Techniques to
Study the Solid State

- Radiotracer diffusion
- Mössbauer Spectroscopy
- Perturbed Angular Correlations
- Muon Spin Rotation μSR
- βNMR
- …



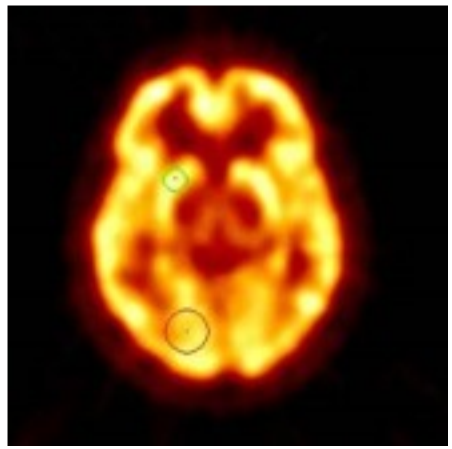
How to study matter with these probes?

Radiotracers

The idea: high energy radiation is *easy to detect*

use radioactive tracer atoms to study: physical, chemical and biological processes

George de Hevesy
Nobel 1943



Positron Emission Tomography

- Radiotracers: presence and location from the high energy radioactive decay products
- μSR and βNMR: *more information* from the anisotropic distribution of the high energy beta particles – correlated with the probe's SPIN – see L2, Brewer
- Yields local magnetic information, like Nuclear Magnetic Resonance (NMR)

Nuclear Magnetic Resonance

(see L4, Percival)

Magnetic Moments of Charged Particles with Spin

$$\mu = g\ \mu_B\ S\ /\ \hbar$$

For the free electron g ~ 2.002, spin is ħ/2, so $\mu \sim \mu_B$

$$\mu_B = \frac{e\hbar}{2m}$$ the Bohr Magneton

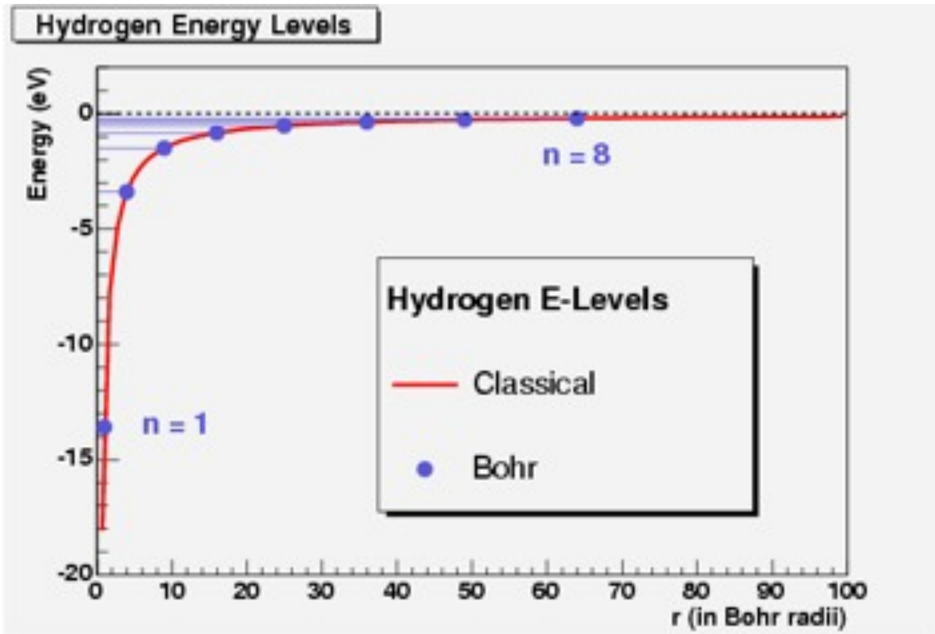
For nuclei, magnetic moment is on the order of the nuclear magneton

$$\mu_N = \frac{e\hbar}{2m_p}$$

i.e. ~2000x smaller!

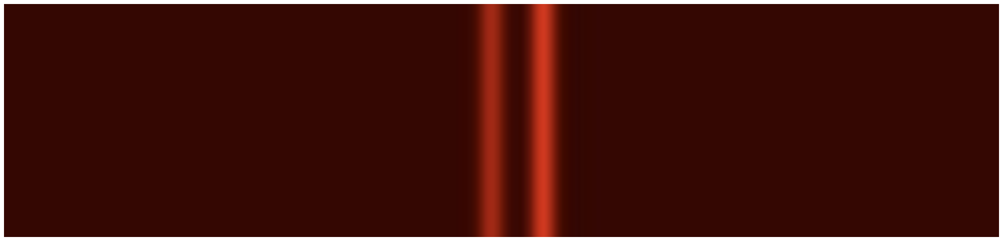
Aside: Structure of Optical Spectra

- Emission of light from H, reflects electron energy level spectrum



Fine and Hyperfine Structure of Optical Spectra

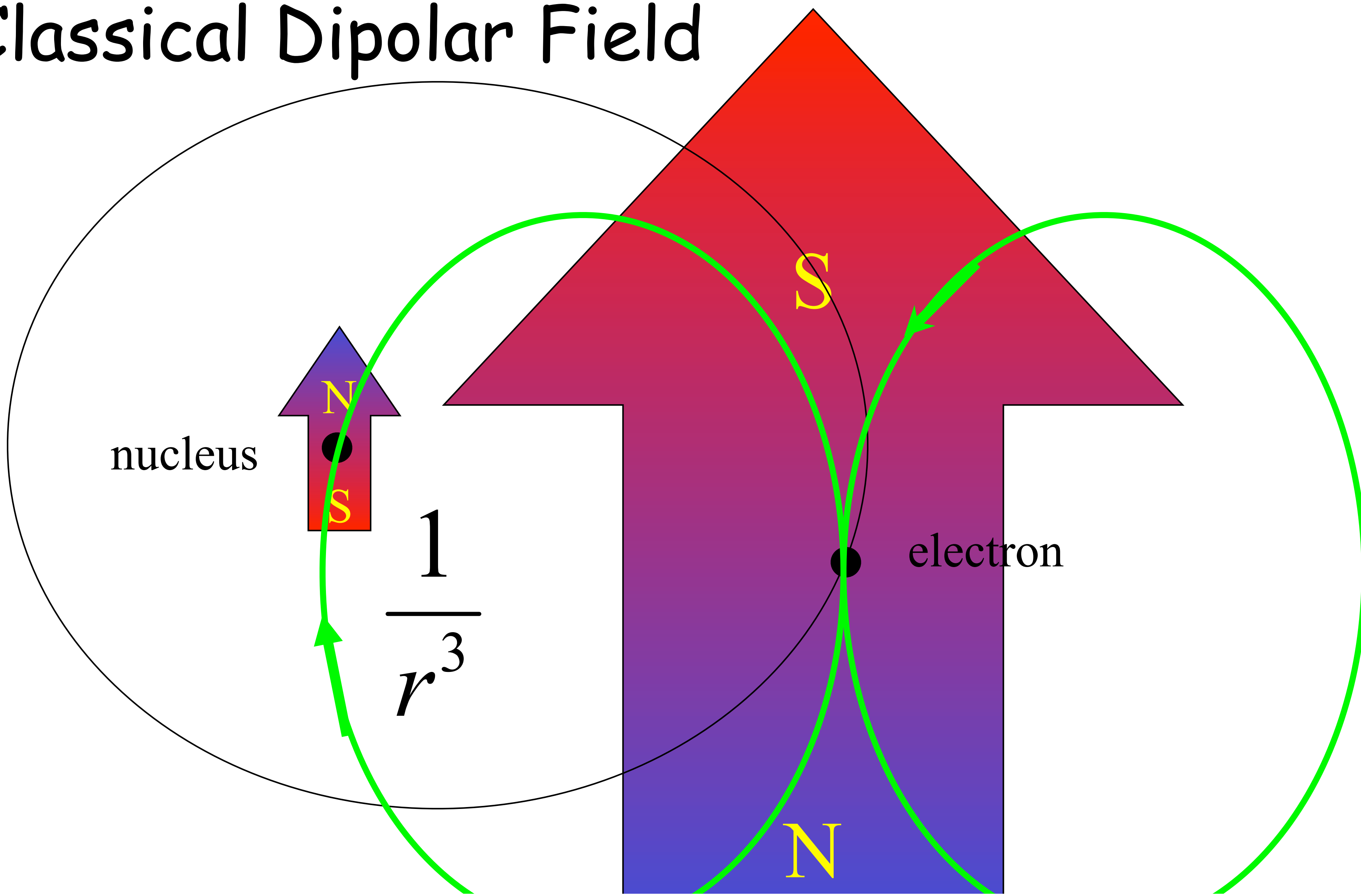
- A closer inspection of optical emission spectra revealed fine and hyperfine structure



- Fine structure: relativistic correction (spin orbit coupling etc.)
- **Hyperfine Structure**: effects of the nuclear magnetic dipole and/or electric quadrupole moments

Hyperfine Interactions

Classical Dipolar Field



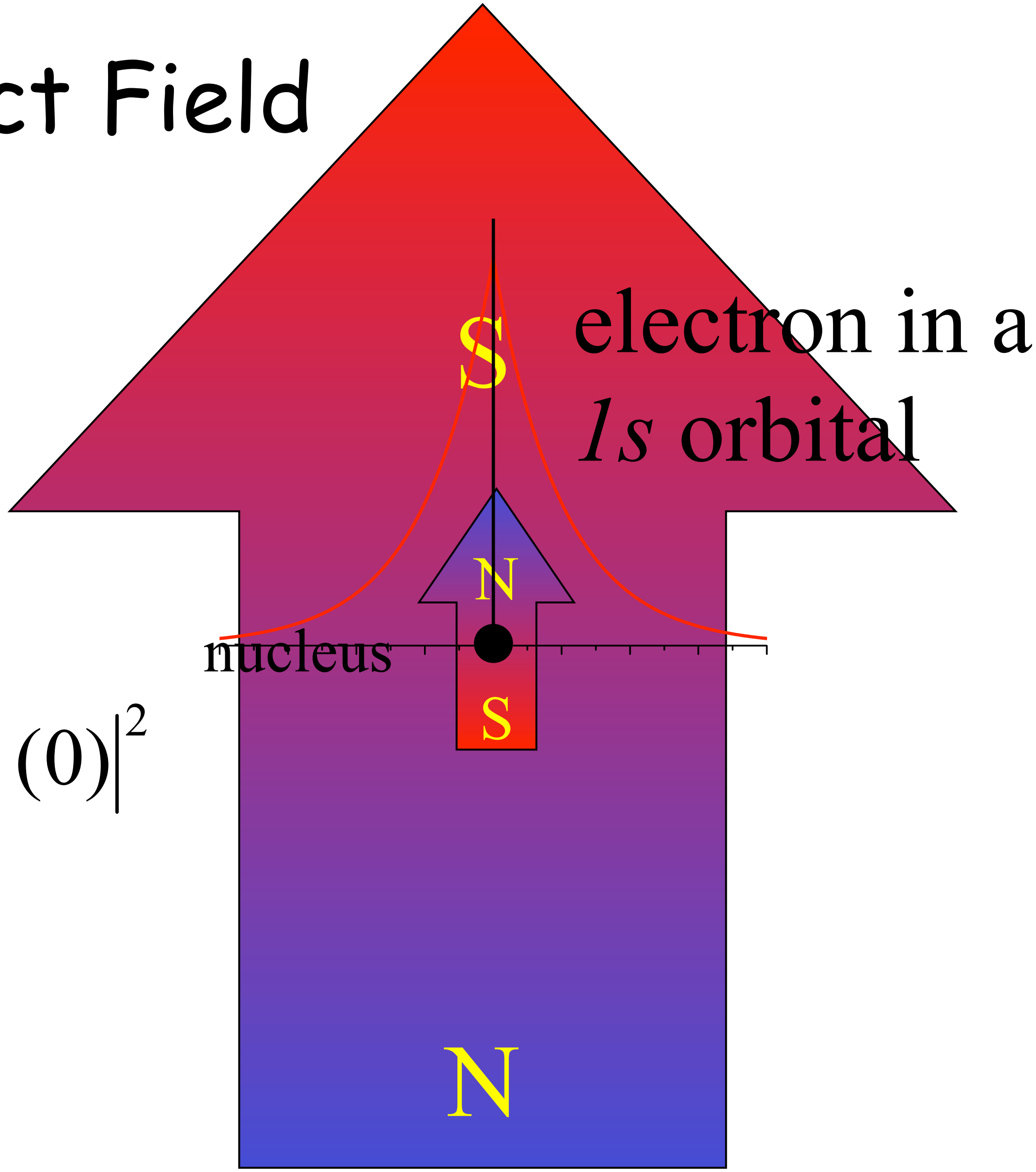
$$\frac{1}{r^3}$$

Hyperfine Interactions

Quantum: Contact Field

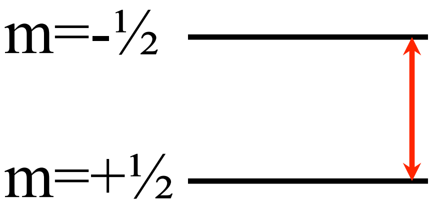
An effective magnetic field:

$$B_{contact} = \frac{8\pi}{3} 2\mu_{Bohr} S \left|\psi(0)\right|^2$$



Zeeman Splitting and Polarization

Potential Energy: $-\vec{\mu} \times \vec{H}$ Zeeman Hamiltonian



$$h\nu_{Larmor} = h\gamma H_0$$

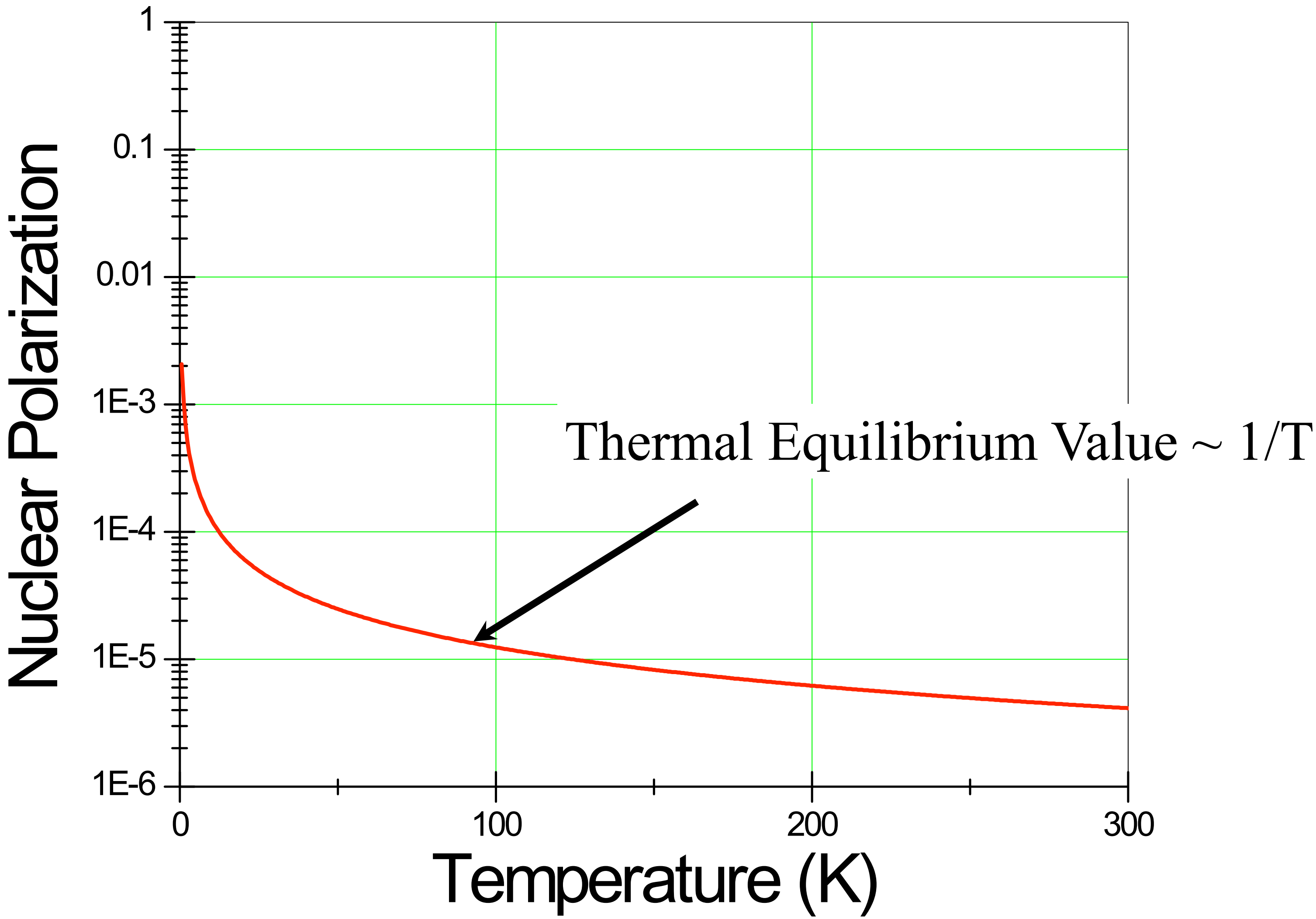
An example of a spin Hamiltonian!

At finite temperature, m=+½ is preferentially populated

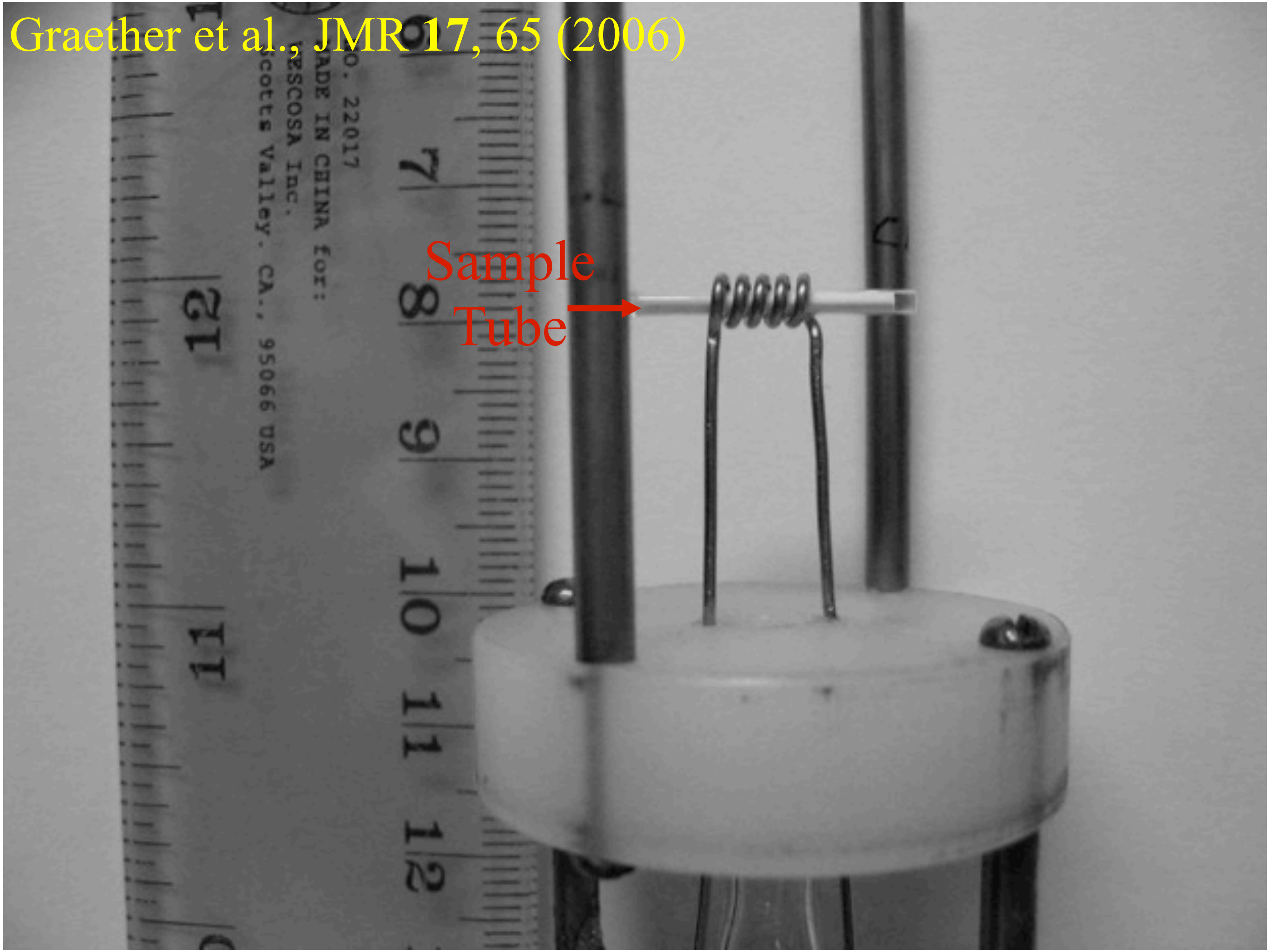
$$\Rightarrow P = c\frac{h\nu_{Larmor}}{k_B T}$$

Nuclear Curie Law

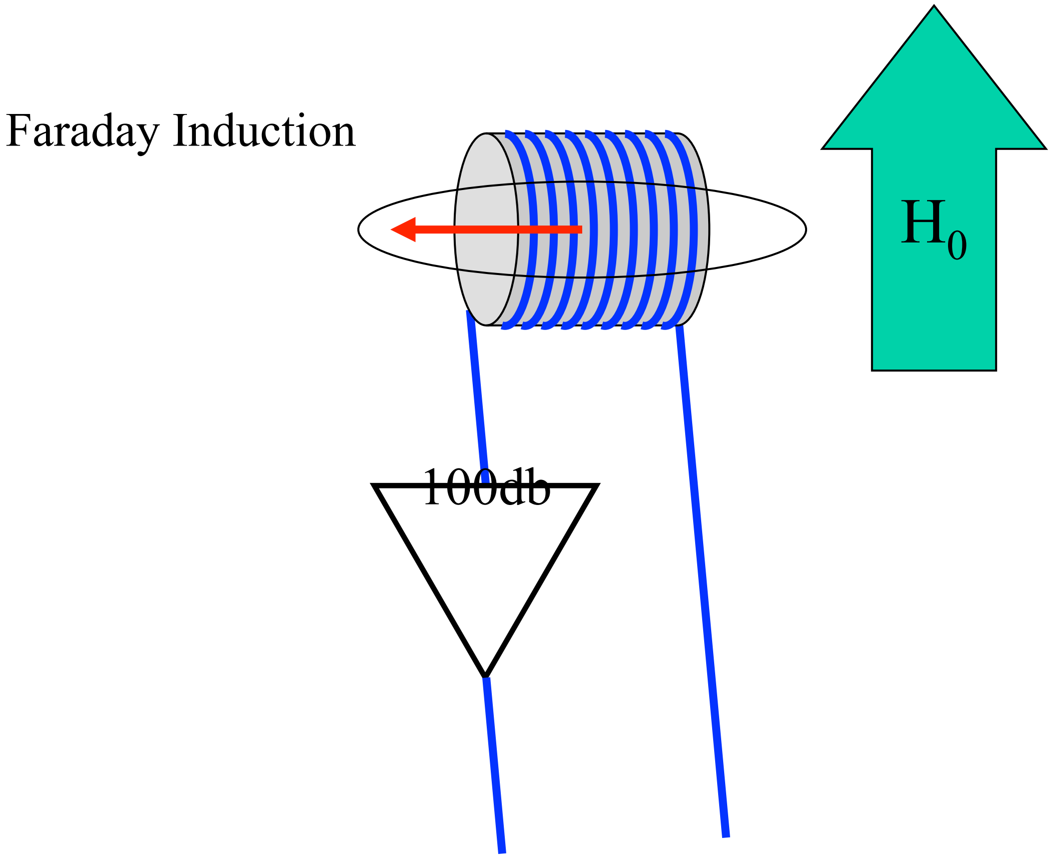
Polarization of ^{8}Li Nuclei in 4.1 T



Conventional NMR detection



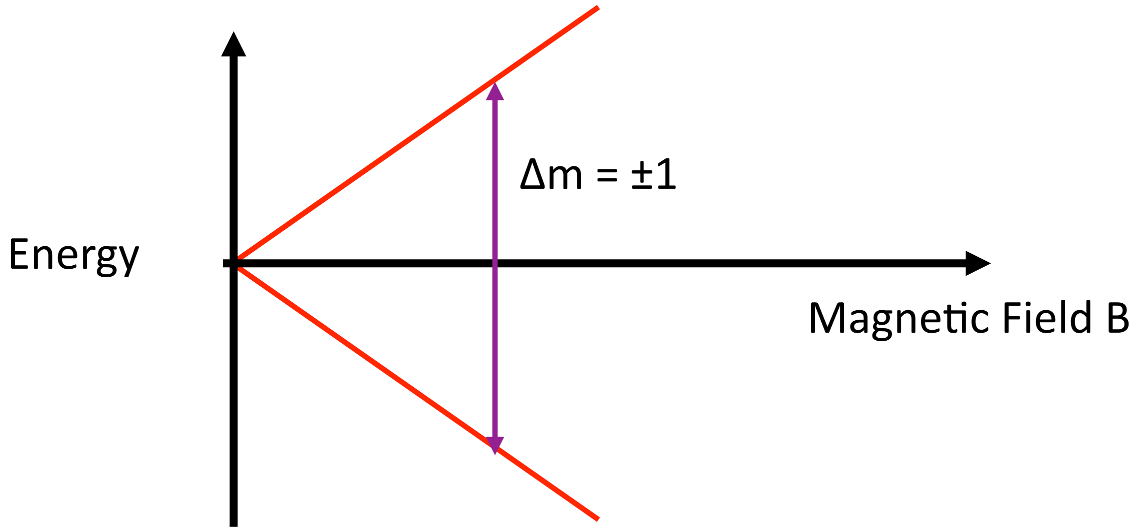
Conventional NMR detection



$$V(t) \propto \nu_{Larmor} \times P \propto (\nu_{Larmor})^2$$

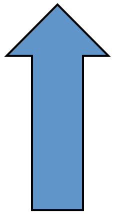
RadioFrequency Field

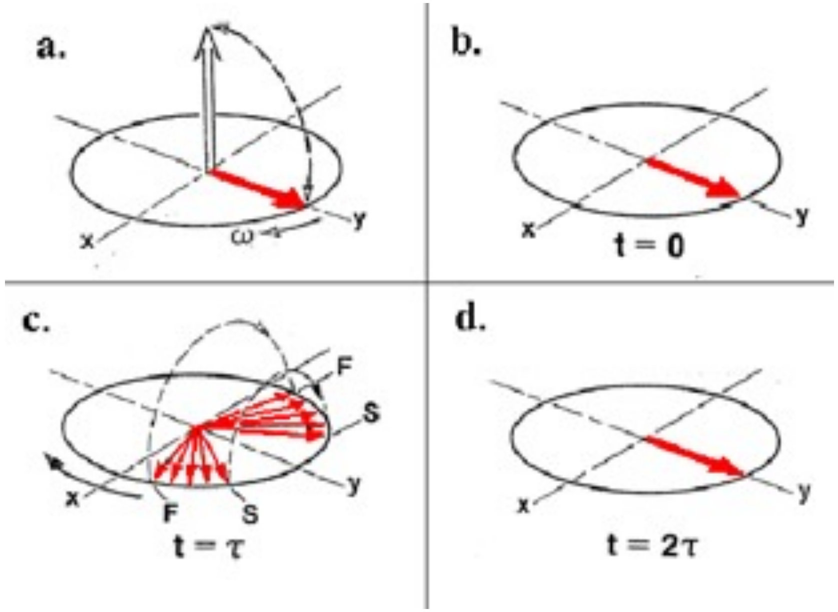
$$\text{Ç} = H_Z + H'_{\mathrm{RF}}(t)$$

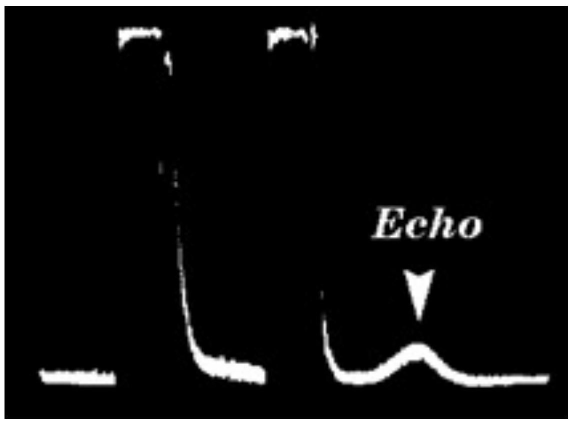


Spin Echos

a big magnetic field polarizes the nuclear spins







Hahn's Spin Echo

Nuclei Spy on Electrons

Electrons produce *magnetic fields* at the nucleus:

via currents (orbital magnetic fields)

via unpaired spins (classical dipolar and contact hyperfine)

$$\vec{H} = \vec{H}_0 + \vec{H}_{loc}(t)$$

<u>Static part:</u> shifts and broadens resonance

<u>Dynamic part:</u> may cause transitions, and relaxation towards equilibrium

Relation to Fundamental Properties

$$\boxed{M = \chi H}$$

Magnetic Susceptibility

$$\chi = \chi' - i\chi''$$

Shift: $\delta = A\chi'(0,0) \longleftarrow$ can be multicomponent and/or inhomogeneous

Relaxation:

$$\frac{1}{T_1} \propto kT \sum_{\vec{q}} A^2(\vec{q}) \frac{\chi''_{\perp}(\vec{q},\omega_0)}{\omega_0}$$

Moriya Expression

In the RF (μeV to zero)

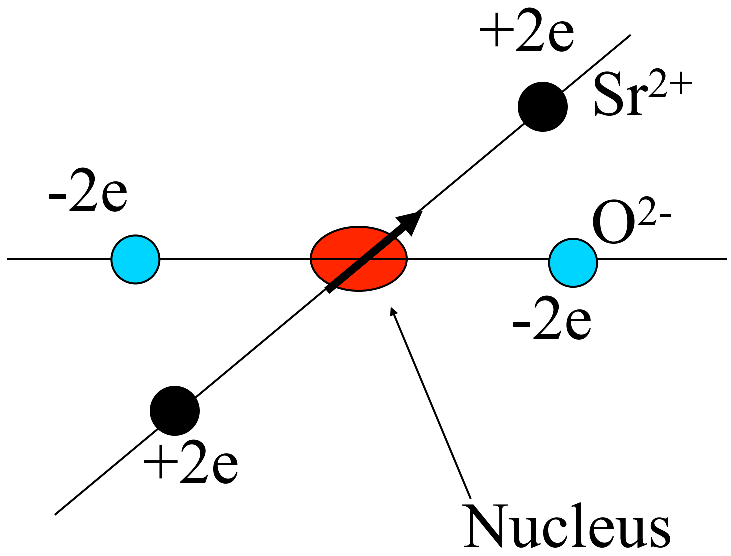
also: quadrupolar effects, diamagnetic shielding, ...

NMR is a point probe of the Magnetic Field

Electric Quadrupole Effects in NMR

Nuclei with spin 0 and ½ have spherical charge distribution ρ(r)

For $I > \frac{1}{2}$, ρ(r) is ellipsoidal with a Quadrupole moment Q



couples the nuclear spin to the local electric field gradient

Scale of Coupling: $$\nu_Q = \frac{3eQV_{zz}}{h2I(2I-1)}$$

EFG = 0 by symmetry for cubic sites

^8Li has I = 2 but Q is quite small

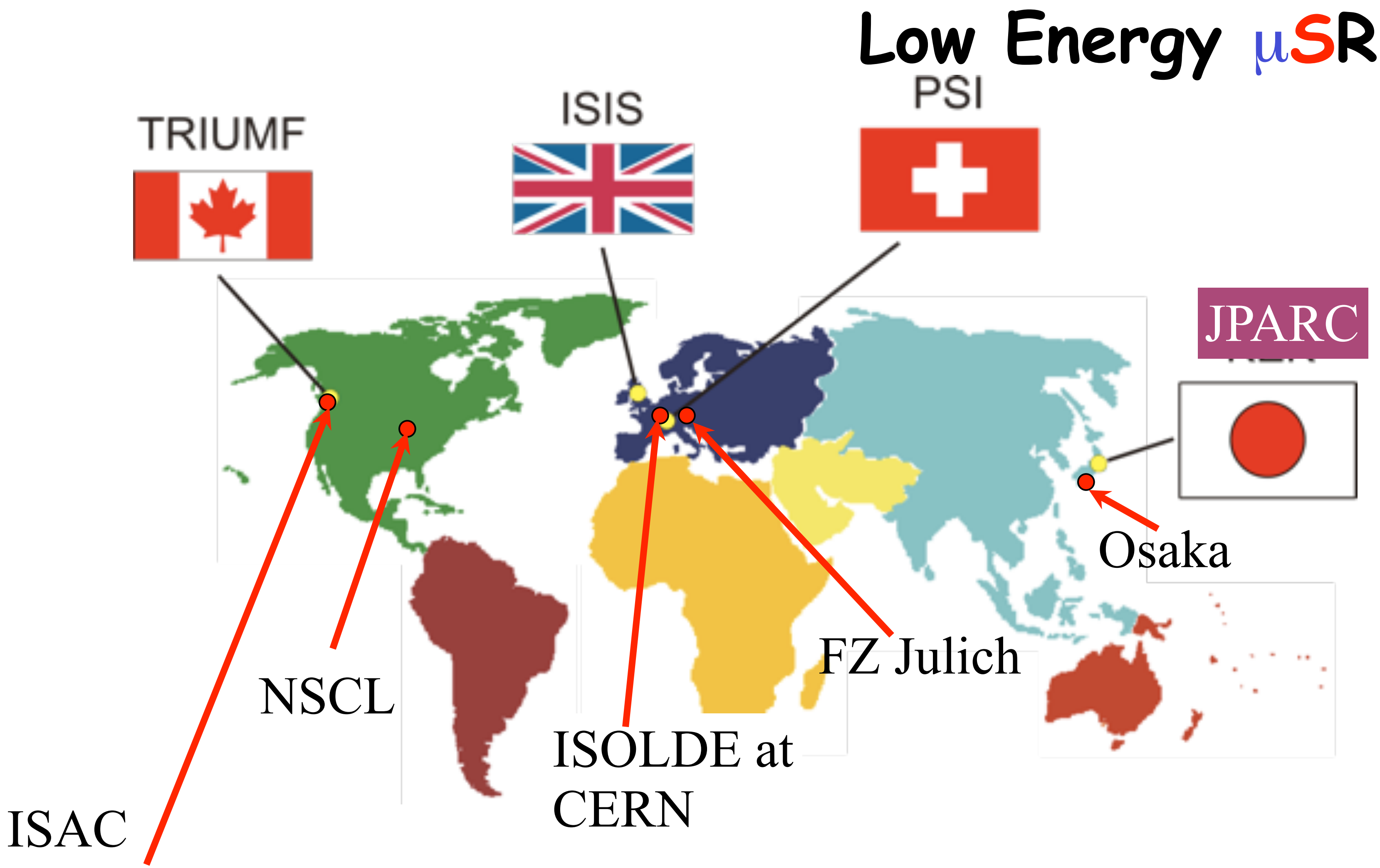
Back to μSR

Some experiments impractical with conventional NMR

Short half-lives means online experiments

βNMR Laboratories

μSR Laboratories:



short halflives: use online experiments

Applications of μSR

μSR

I. The muon as a microscopic probe of magnetism

II. Muonium as a light Hydrogen isotope
(Mu = μ^+e^- - see L9)
(H = p^+e^-)

- Magnetically ordered materials
- Magnetically frustrated and glassy systems

(L6,8, Luke)

- Superconductors (mostly vortex state)

(L12,14, Sonier)

- …

- Chemical Reaction Kinetics

(L10, Percival)

- Muoniated Radicals

(L13, McKenzie)

- Quantum Diffusion
- Hydrogen in Semiconductors

(L11, Chow)

- Soft Matter

(L19, McKenzie)

- …

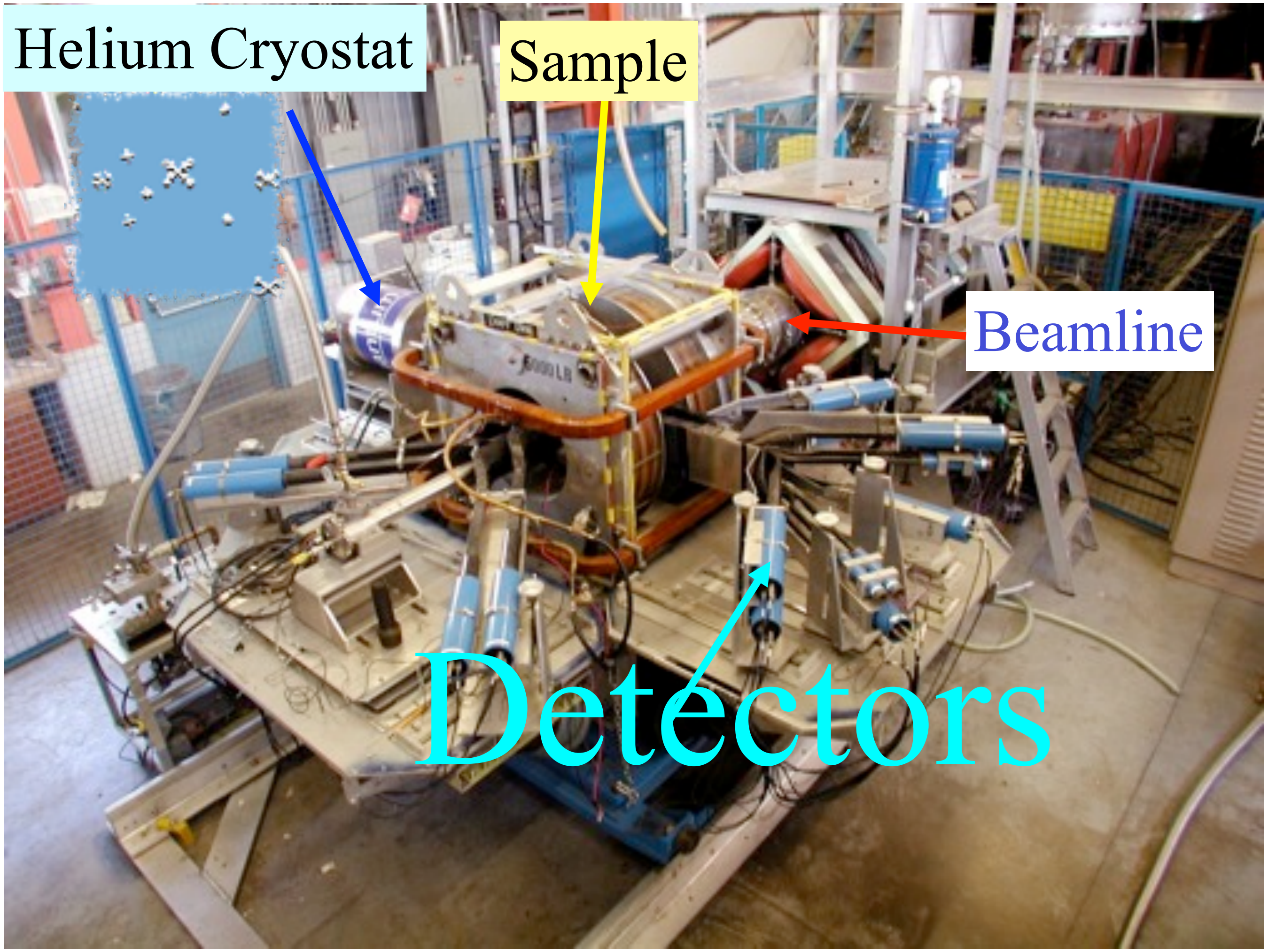
Applications of βNMR and Low Energy μSR

- Probe penetration variable:

~200 nm to ~2 nm: depth resolution!

- Heterostructures
- Buried Interfaces
- Near surface effects
- Thin films
- See L15, L17 Kiefl and L20 MacFarlane

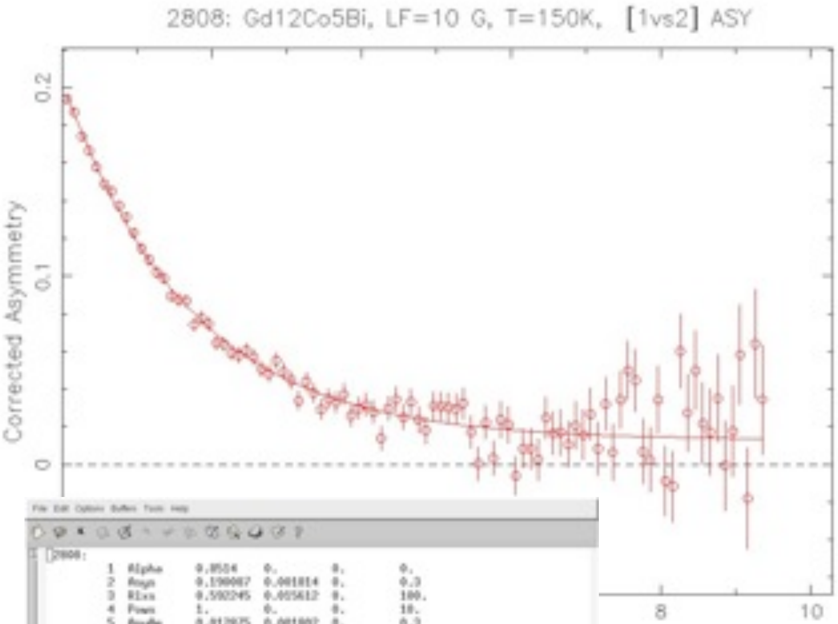
How to do μSR

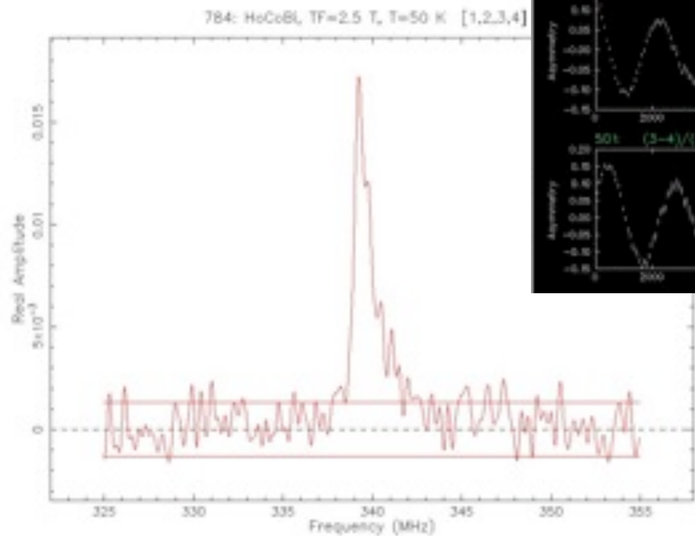


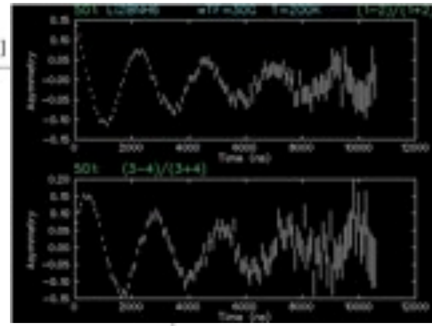
- See practical sessions and L5, Kreitzman

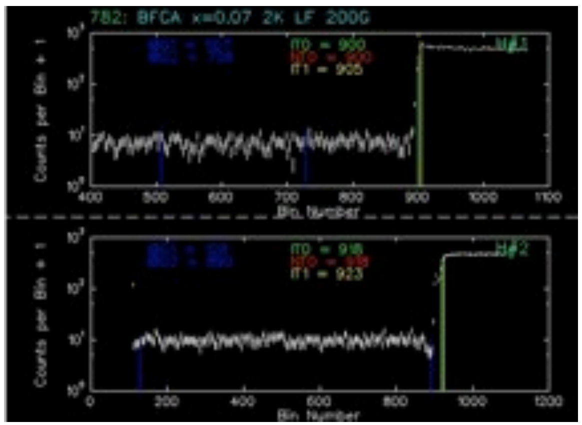
How to Analyze μSR Data

See practical session P2 etc, Brewer









Professional Organizations

- International Society of Muon Spin Spectroscopy (ISMS)
- TRIUMF User's Group http://www.triumf.ca/triumf-users-group

Thanks!

- **Lecturers:** J. Brewer, J. Sonier, G. Luke, R. Kiefl, K. Chow, T. Uemura, S. Kreitzman, P. Percival, I. McKenzie
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